Ferrofluid Pivot Bearing

This application claims the benefit of Japanese Patent Application No. 2001-125887, filed April 24, 2001, and Japanese Patent Application No. 2001-160349, filed May 29, 2001.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to bearings used to support rotatable assemblies. Particularly, the present invention relates to bearings used in hard disk drives. More particularly, the present invention relates to pivot bearings used in hard disk drives.

2. Description of the Prior Art

The extensive data storage needs of modern computer systems require large capacity data storage devices. A common storage device is the rotating magnetic disk drive. A disk drive typically contains one or more flat disks that are rigidly attached to a common spindle. The disks are stacked on the spindle parallel to each other and spaced apart so that they do not touch. The disks and spindle rotate in unison at a constant speed provided by a spindle motor. A disk drive incorporates a solid disk-shaped substrate with a center hole to accommodate the spindle. The substrate is coated with a thin layer of magnetizable material. Data is recorded on the surfaces of the disks in the magnetizable layer.

The recorded data is usually arranged in circular concentric tracks, which are further divided into a number of sectors. Each sector forms an arc of a track and all the sectors of a track form a circle. A movable actuator positions a transducer head adjacent the data surface to read or write data. Most disk drives now being produced use a rotary actuator that pivots about an axis. There is one transducer head for each disk surface designed to contain data. The transducer head is an aerodynamically-shaped block of material on which is mounted a magnetic read/write transducer. The block travels above the surface of the disk at an extremely small distance as the disk rotates. The close proximity to the disk surface is critical in enabling the transducer to read from or write to the data in the magnetizable layer.

A rotary actuator typically includes a solid block near the pivot axis having comb-like arms extending toward the disk, a set of thin suspensions attached to the arms, and an electromagnetic motor on the opposite side of the axis. The transducer heads are attached to the suspensions, one head for each suspension. The actuator motor rotates the actuator to position the head over a desired data track. Once the head is positioned over the track, the constant rotation of the disk will eventually bring the desired sector adjacent the head allowing the data to be read or written.

Conventionally, the rotatable disk spindle assembly and the rotary actuator assembly are supported by sets of ball bearings housed in annular races. Typically, there are two sets of bearings for the disk spindle and two for the rotary actuator. Each set supporting a particular assembly that is axially separated from the other to

provide greater stability. Multiple balls, however, generate significant bearing drag and mechanical hysteresis.

One such problem is contamination from the bearing grease caused by evaporation or migration. This contamination may affect the head/disk interface. The head and disk may be damaged by the evaporated substance from the bearing. Another problem relates to the movement of the pivot bearing. The rotatable actuator moves within an angle of about 30 degrees of repetition. During this movement, especially at startup and turning, pulse-like force is generated by the ball bearings in the pivot. This force is then transmitted to the read/write heads as high frequency wave noise. This affects precise head positioning and is recognized as error of the servo track signal. This results because of poor damping effect of the ball bearings in the pivot.

Yet another problem is that the balls in the ball bearing have a tendency to be fretted by poor lubrication during the small repetitive movement of the pivot bearing. Further, the performance of ball bearings depends highly on the accuracy of the individual parts such as the balls and the inner/outer races.

Although the oil bearing is currently being developed as an improved alternative to the ball bearing for spindle motor applications, it may not be applicable to the pivot bearing due to the pivot bearing's small repetitive movements within a 30 degree arc of movement. The oil pressure generated by this small repetitive movement is insufficient to support the head arm assembly. Furthermore, the oil itself may create oil contamination problems if not sealed properly.

A typical, prior-art ball bearing is shown in Figure 1. An actuator (not shown) is typically mounted to a motor-driven pivot shaft **4** of a ball-bearing pivot **1**, which rotates the heads on the actuator to various locations on the disk (not shown). Shaft **4** is surrounded by a housing **3**. Typically, two ball bearings **2** are used to support shaft **4** within housing **3**. To reduce the likelihood of emitting oil vapor and aerosol droplets of grease that are potential source of contamination in the disk drive, prior art devices have used several different types of seals to seal the pivot bearings. One type of bearing seal, known as a ferrofluid seal, is practically impermeable to emissions from bearings.

US Patent No. 6,229,676 B1 (2001, Walter Prater) discloses a ferrofluid seal for a hard disk drive actuator bearing. The ferrofluid seal has two circular plates that are axially spaced apart about a nonmagnetic pivot shaft of the actuator. The plates are parallel and in close proximity to one another. The upper plate is made of magnetically-conductive steel and is mounted to a stationary sleeve, which surrounds the shaft. The lower plate is mounted to the shaft and has an annular magnet with pole pieces on an upper surface. A magnetic ferrofluid is located between the magnet and the upper plate to complete the magnetic circuit and form a seal.

A disadvantage of using such a ferrofluid seal with conventional pivot bearings is the incorporation of additional parts to the actuator bearing assembly. Additional parts include higher attendant material and labor costs. Further, the ball bearings

still have the problems associated with ball bearing pivot bearings previously enumerated.

With the development of faster and more powerful computer systems, there has been a corresponding demand for improved storage devices. Typically, these demands translate to a desire for reduced cost, increased data capacity, increased speed at which disk drives operate, reduced electrical power consumption by the disk drives, and increased resilience of the disk drives in the presence of mechanical shock and other disturbances.

Therefore, what is needed is a pivot bearing that is simple to construct. What is further needed is a pivot bearing that is capable of providing contamination control, high damping effect and noiseless performance. What is still further needed is a pivot bearing that is substantially free of fretting wear. What is yet further needed is a pivot bearing that allows higher precision in repetitive, positional performance that is capable of contributing to higher memory densities of hard disk drives.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a ferrofluid pivot bearing that is capable of providing contamination control. It is another object of the present invention to provide a ferrofluid pivot bearing that provides high damping effect and substantially noiseless performance. It is a further object of the present invention to provide a ferrofluid pivot bearing that is substantially free of fretting wear. It is yet another object of the present invention to provide a pivot bearing that allows higher

precision in repetitive positional performance when the repetitive positional performance is limited to movement within an acute angle. It is also another object of the present invention to provide a ferrofluid pivot bearing that provides enough stiffness to support an actuator head and arm by using the magnetic levitation phenomenon provided by the combination of ferrofluid, magnet, magnetic yokes and nonmagnetic housing.

The present invention achieves these and other objectives by providing a ferrofluid pivot bearing comprising a shaft, at least a first magnetic element fixedly attached to the shaft, a housing containing the at least a first magnetic element in which the housing is rotatable about the at least a first magnetic element, and a quantity of magnetic fluid inside the housing between the first magnetic element and the inside surface of the housing. Optionally, a magnetic coating over at least a portion of the outside surface of the housing is provided. The shaft is made from a non-magnetic material. The first magnetic element has a cylindrical shape with a central hole sized to receive the shaft in a sliding fit. The first magnetic element is fixed to the shaft to prevent its rotation about the shaft. Generally, the first magnetic element is a magnet.

An oil repellent material may be used to help prevent migration of the ferrofluid out of the housing. It is optionally applied to an area of the shaft that corresponds to the ends of the housing, to an area of the ends of the housing that correspond to the shaft, or to both corresponding areas of the shaft and the ends of the housing. The oil repellent material is a material, preferably a fluoropolymer, that

reduces the wetting ability of the ferrofluid between the shaft and the ends of the housing.

The magnetic coating over at least a portion of the outside surface of the housing is generally at least one of nickel, iron and nickel-iron alloy. The magnetic coating reduces the magnetic flux leakage from the pivot bearing. Excessive magnetic flux leakage in a hard disk drive has an adverse effect on the operation of the read-write heads of the disk drive. The magnetic coating may cover all of the major outside surfaces of the housing including the top and bottom surfaces, or it may cover only the circumferential surface of the housing. The coating may be disposed on the housing by plating, deposition or spattering.

It is the magnetic levitation phenomenon of the present invention that allows the present invention to work without the use of ball bearings. With the use of one or more magnetic elements, the magnetic fluid and the non-magnetic housing, the magnetic flux density generates sufficient stiffness within the pivot bearing to support the head arm actuator of a disk drive even when the actuator is limited to an angle of thirty degrees as a repetitive movement operation. The combination of components in the present invention also provides contamination control, high damping effect and noiseless performance. The use of ferrofluid seal technology creates a liquid, hermetic seal that prevents the escape of potential contaminants from inside the housing. The viscosity of the ferrofluid and the fact that, unlike the prior art ball-bearing pivot, the magnet of the present invention does not contact the housing

directly provides the high damping effect and contributes to the noiseless operation of the present invention.

Further, the use of magnetic fluid and at least one magnetic element provides a non-fretting characteristic to the ferrofluid pivot bearing. Because the prior art ball-bearing pivot operates on the principal that the ball bearings ride on the shaft, surface damage may result. This surface damage, called fretting corrosion, is caused by the close contact under pressure of the two surfaces, one or both of which are metals, and subjected to a slight relative motion. The magnetic phenomenon of the present invention coupled with the magnetic fluid in the gap between the magnetic element and the housing provides a pivot bearing that lacks the close contact of the two surfaces and, thus, helps prevent fretting corrosion.

In use, both the prior art pivot bearing and the present invention generate vibration. However, the present invention generates a much lower vibration than the frequency peaks produced by the ball bearing pivot of the prior art. The viscosity of the ferrofluid coupled with the levitation phenomenon provides the damping effect previously described. This reduces the frequency wave of repetition movement up to several kilohertz (kHz). The frequency wave peaks generated by the prior art ball-bearing pivot may be adverse to the positioning of read/write heads.

These characteristics allow the ferrofluid pivot bearing of the present invention to operate within a wide range from a large stroke repetition to a small stroke repetition, which is extremely useful for tracking purposes in hard disk drive read/write operations. These characteristics also allow the pivot bearing of the

present invention to have high precision performance regarding the repetitive movement of hard disk drive actuator arms. Having a high repetitive movement performance contributes to the capability of using higher memory densities in hard disk drives or any high-density removable and/or floppy disk drives.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a cross-section view of a prior art pivot bearing.

FIGURE 2 is a cross-sectional view of one embodiment of the present invention showing three magnetic elements with four bearing elements attached to a shaft in a housing with a magnetic layer disposed on its circumference.

FIGURE 3 is a cross-sectional view of a second embodiment of the present invention showing one magnetic element with two bearing elements attached to a shaft in a housing with a magnetic layer disposed on its circumference.

FIGURE 4 is a cross-sectional view of a third embodiment of the present invention showing three magnetic elements with two bearing elements attached to a shaft in a housing with a magnetic layer disposed on all of the outside major surfaces of the housing.

FIGURE 5 is a cross-sectional view of a fourth embodiment of the present invention showing one magnetic element attached to a shaft in a housing with a magnetic layer disposed on all of the outside major surfaces of the housing.

FIGURE 6 is a graphical representation of the frequency response of the present invention and a prior art pivot bearing.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The preferred embodiments of the present invention are illustrated in Figs. 2-6. Figure 2 shows a cross-sectional view of one embodiment of a ferrofluid pivot bearing **10** of the present invention. Ferrofluid pivot bearing **10** includes a shaft **12** having a first magnetic element **14**, a second magnetic element **16** and a third magnetic element **18** fixedly attached to shaft **12**. Inner bearing elements **20** are fixedly attached to shaft **12** between first, second and third magnetic elements **14, 16** and **18**, respectively. Outer bearing elements **22** are also fixedly attached to shaft **12** at the outside surfaces of first magnetic element **14** and third magnetic element **18**. First, second and third magnetic elements **14**, **16** and **18**, inner bearing elements **20** and outer bearing elements **22** each have a cylindrical shape similar in appearance to a disk or a donut.

The shaft **12**, magnetic elements **14, 16** and **18**, inner bearing elements **20**, and outer bearing elements **22** form shaft assembly **30**. Shaft assembly **30** is enclosed in a housing **24**. The inside dimensions of housing **24** and the outside

dimensions of shaft assembly **30** are sized such that a small gap **32'** between the bearing elements **20** and the inside diameter of housing **24** is created, a somewhat larger gap **32** between magnetic elements **14**, **16** and **18**, bearing elements **22** and the inside diameter of housing **24** is created, and a gap **33** between bearing elements **22** and the ends of housing **24** is created. Gaps **32**, **32'** and **33** are not to scale but shown larger than normal for clarity. A magnetic fluid (not shown) is incorporated within housing **24** filling a large proportion of the space defined by gaps **32**, **32'** and **33**. The viscosity of the magnetic fluid and the magnetic flux density created by magnet elements **14**, **16** and **18** generate sufficient stiffness in the pivot bearing **10** to support the head/arm actuator even when the actuator is limited to an angle of approximately 30° as a repetitive movement operation. A layer **28** of magnetic material is optionally disposed around the outside of housing **24**. Magnetic layer **28** is generally at least one of nickel, iron and nickel-iron alloy. The magnetic coating reduces the magnetic flux leakage from the pivot bearing

Magnetic elements **14**, **16** and **18** have north and south poles and are positioned on shaft **12** such that adjacent magnetic elements have similar magnetic poles facing each other. As illustrated, the south pole end of magnetic element **16** is positioned to be adjacent to the south pole end of magnetic element **14**, i.e. creating a repulsive force instead of an attractive force between magnetic elements. This arrangement is important in multi-magnet pivot bearings of the present invention to maintain the proper alignment of magnetic flux fields for use with the magnetic fluid within housing **24** to retain the magnetic fluid's proper position between the magnets

and the inside surface of housing **24**. It is noted that the magnetic elements **14**, **16** and **18** may be inverted so long as all magnetic elements are inverted to maintain the alignment described, i.e. the same magnetic poles are facing each other in adjacent magnetic elements.

Shaft **12** and housing **24** are made of non-magnetic material. Housing **24** is shown as a two-part housing system that has a housing body **25** with a body end flange **26** and a housing end cap **27** for enclosing shaft assembly **30** within housing **24**. Body end flange **26** and housing end cap **27** have central openings sized to accept the outside diameter of shaft **12**. Inner bearing elements **20** and outer bearing elements **22** are made of magnetic material and further serve as pole pieces, as that term is understood by those skilled in the art of ferrofluid magnetic seals. Optionally, an oil repellent coating (not shown) may be applied to shaft **12** along circumferential areas indicated by reference numeral **34**. An oil repellent coating may also be applied to a corresponding circumferential area **36** on the body end flange **26** and housing end cap **27**, which is the circumferential area on the inside of the central openings. The oil repellent coating is preferably made of a fluoropolymer material.

An example of preferred dimensions for a ferrofluid pivot bearing of the present invention for use in a 3.5 inch disc drive includes a shaft **12** being about 16.5 mm long with a diameter of about 4.0 mm diameter, magnetic element **16** being about 4.0 mm long with a diameter of about 8.0 mm, magnetic elements **14** and **18** being about 2.0 mm long with a diameter of about 8.0 mm, inner bearing elements

20 being about 1.5 mm long with a diameter of about 8.5 mm, outer bearing elements being about 0.10 mm long with a diameter of about 8.0 mm. The inside diameter of housing **24** is about 8.5 mm and the inside distance between body end flange **26** and housing end cap **27** is about 11.24 mm. It is preferable that gap **32'** formed is about 7 micrometers to about 16 micrometers, or, in other words, the difference between the inside diameter of housing **24** and the outside diameter of inner bearing elements **20** is about 14 micrometers to about 32 micrometers. It is also preferable that gap **33** between outer bearings **22** and body end flange **26** and housing end cap **27** is about 20 micrometers. It is understood by those skilled in the art that these dimensions may be different for disc drives of different sizes such as 1 inch, 1.8 inch and 2.5 inch disc drives and that the determination of these dimensions are well within the ability of those skilled in the art without undue experimentation.

Turning now to Fig. 3, there is shown another embodiment of the present invention. Ferrofluid pivot bearing **50** includes a shaft assembly system **55** enclosed in a housing system **60**. Shaft assembly system **55** includes a shaft **56**, a first magnetic element **57** attached to shaft **56**, and a pair of outer bearing elements **58**. Outer bearing element **58** is made of a magnetic material while shaft **56** is made of a non-magnetic material. The outer bearing elements **58** and magnetic element **57** are sized to create gaps **69**, **69'** and **69"**. Unlike the outer bearing elements **22** in the embodiment illustrated in Fig. 2, outer bearing elements **58** are sized to provide a

gap **69'** between the outer bearing elements **58** and the inside diameter of housing **24** like that of gap **32'** in Fig. 1.

Housing system **60** includes a housing body **62** with a body end flange **64** and a magnetic layer **66** disposed around the circumference of housing body **62**. Housing end cap **68** is fitted to the open end of housing body **62** to enclose shaft assembly system **55** within housing system **60**. As in the first embodiment, a magnetic fluid (not shown) is added to pivot bearing **50**. This embodiment of the present invention may also have an oil repellent coating around the circumference of shaft **56** in designated area **70** as well as a coating around the inside surface **72** of the openings in the housing end flange **64** and the housing end cap **68**.

Fig. 4 illustrates a third embodiment of the present invention showing a ferrofluid pivot bearing **80** of the present invention. Pivot bearing **80** includes a shaft assembly **82** and a housing assembly **95**. Shaft assembly **82** includes a first magnetic element **84**, a second magnetic element **85** and a third magnetic element **86** attached to a shaft **87**. Between magnetic elements **84**, **85** and **86** are inner bearing elements **89** and **90**, respectively. Inner bearing elements **89** and **90** are made of a magnetic material, which also act as pole pieces. Unlike the embodiment illustrated in Fig. 2, ferrofluid pivot bearing **80** does not have any outer bearing elements.

Housing assembly **95** includes housing body **97** with a body end flange **98**, and a housing end cap **100** for enclosing magnetic elements **84**, **85** and **86**, and inner bearing elements **89** and **90**. Housing assembly **95** also contains magnetic

fluid (not shown) between the magnetic elements, the inner bearing elements and the inside diameter of housing assembly **95**. A magnetic layer or coating **102** is disposed on all major outside surfaces of housing assembly **95** including body end flange **98** and housing end cap **100**. Pivot bearing **80** optionally has an oil repellent coating around the circumference of shaft **87** in an area designated by reference numeral **104**. An oil repellent coating may also be disposed along an area of the opening in body end flange **98** and housing end cap **100** designated by reference numeral **106**. The main difference between the embodiments in Figs. 2 and 4 is the absence of outer bearing elements in the embodiment in Fig. 4 and the extent of the coverage of the magnetic layer or coating. Any combination of the use of bearing elements and magnetic layer coverage may be used. In Fig. 4, magnetic elements **84** and **86** act as the outer bearing elements and, thus, are sized to provide a gap **88** between magnetic elements **84**, **86** and the ends of housing assembly **95**.

Fig. 5 illustrates a fourth embodiment of the present invention and is the simplest and least expensive to manufacture in terms of material and labor. Ferrofluid pivot bearing **120** includes a shaft assembly **122** and a housing assembly **130**. Shaft assembly **122** includes a magnetic element **124** attached to a shaft **126**. Housing assembly **130** includes a housing body **132** having a body end flange **134**, and a housing end cap **136** for enclosing magnetic element **124** within housing assembly **130**. A magnetic layer or coating **140** is disposed on all major outside surfaces of housing assembly **130** including body end flange **134** and housing end cap **136**. Pivot bearing **120** may optionally have an oil repellent coating along an

area of shaft **126** designated by reference numeral **142**. An oil repellent coating may also be disposed along an area of the opening in body end flange **134** and housing end cap **136** designated by reference numeral **144**. A magnetic fluid (not shown) is contained within housing assembly **130** and captured between the outside surface of magnetic element **124** and the inside surface of housing assembly **130**. Magnetic element **124** also acts as the bearing element in ferrofluid pivot bearing **120**.

The choice of embodiments to use is driven by factors such as ease of manufacture, cost of manufacture and pivot bearing performance. Applications where ease and cost of manufacture are critical, embodiments illustrated in Figs. 3 and 5 are preferred. Applications where pivot bearing performance such as bearing stiffness is the guiding characteristic, embodiments illustrated in Figs. 2 and 4 are preferred.

Figure 6 illustrates a comparison of frequency response of the ferrofluid pivot bearing of the present invention (B) and the ball bearing pivot of the prior art (A). As can be seen from Fig. 6, the ball bearing pivot (A) exhibits frequency peaking while the present invention (B) provides relatively peak-free response. The graph shows that vibration generated by the ferrofluid pivot bearing of the present invention is very much lower than that of the ball bearing pivot. It is the high damping effect provided by the viscosity of the ferrofluid as well as the levitation force provided by the magnetic flux density of the magnetic element(s) that reduces frequency wave peaking of repetition movement up to several kilohertz.

As discussed previously, the major advantages of the present invention are contamination control, high damping effect, noiseless performance, and its non-fretting characteristic. Using the magnetic flux force (i.e. the force responsible for the levitation phenomenon) combined with the magnetic fluid as the bearing shaft support in a ball bearing-less pivot bearing has not heretofore been provided.

Although the preferred embodiments of the present invention have been described herein, the above description is merely illustrative. Further modification of the invention herein disclosed will occur to those skilled in the respective arts and all such modifications are deemed to be within the scope of the invention as defined by the appended claims.